

# Smoke Plume Trajectory from *In Situ* Burning of Crude Oil: Complex Terrain Modeling

Kevin B. McGrattan  
National Institute of Standards and Technology  
Gaithersburg, Maryland 20899 USA

## Abstract

As part of the process of obtaining preapproval for the use of *in situ* burning in the event of an oil spill, numerical models have been used to predict the concentration of particulate matter or other combustion products downwind of the fire. The NIST model, ALOFT (A Large Outdoor Fire plume Trajectory), is based on the conservation equations that govern the introduction of hot gases and particulate matter from a large fire into the atmosphere. Because it is based on the fundamental equations rather than empirical correlations, simulations of burning in areas of very mountainous terrain, like the southern Alaskan coast, can be handled very easily using digitized terrain data at roughly 100 m resolution. The model has been applied to regions in Alaska, and predictions of distances from the fire where combustion product concentrations fall below ambient air quality standards have been made.

## 1.0 Introduction

Several regions of the United States, Canada and Europe are presently evaluating the feasibility of using *in situ* burning as a remediation method for oil spills. A particular concern of local authorities is the possibility of exposing populations to particulate concentrations in excess of ambient air quality standards. To address this issue, the National Institute of Standards and Technology (NIST), under the sponsorship of the US Minerals Management Service and the Alaska Department of Environmental Conservation, has conducted a research program over the past decade to assess the burning characteristics of large crude oil fires on water (Evans *et al.*, 1993). The program has consisted of laboratory and mesoscale measurements of burning and emission properties of various heavy fuels, and the development of a numerical model to predict the downwind concentration of various combustion products whose emission factors are measured from large-scale experiments.

The ALOFT, short for "A Large Outdoor Fireplume Trajectory," model<sup>1</sup> has been designed to predict the downwind and lateral extent of ground-level concentrations of combustion products that might exceed ambient air quality standards. The combustion product most likely to exceed standards is PM<sub>10</sub> particulate. In the United States, the ambient air quality standard for PM<sub>10</sub> is 150  $\mu\text{g}/\text{m}^3$  averaged over 24 hours. For the purpose of *in situ* burn planning, the 24 hour average has been reduced to 1 hour. Calculations performed for the State of Alaska showed that for a variety of meteorological conditions typical of the North Slope and Cook Inlet, hour-averaged particulate concentrations found at the ground downwind of a fire consuming about 95 m<sup>3</sup> (600 bbl) of crude oil per hour would not exceed 150  $\mu\text{g}/\text{m}^3$  (hour averaged) beyond 5 km (Mc-

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<sup>1</sup>In previous reports, the model was referred to as the Large Eddy Simulation (LES) model because much of the numerical methodology originated with enclosure fire models developed at NIST.

Grattan *et al.*, 1995). However, these calculations did not take into account the very mountainous terrain of parts of Alaska. Thus, the original flat terrain distance predictions have been supplemented with additional predictions that incorporate varying terrain heights.

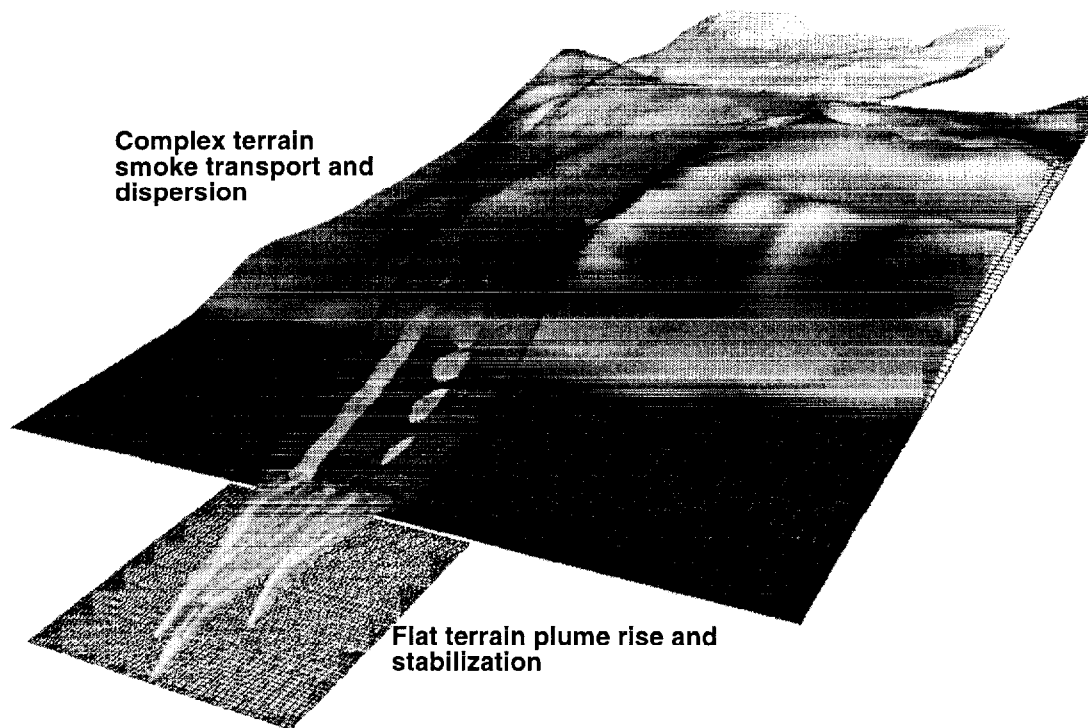
## 2.0 Mathematical Model

A detailed description of the flat terrain version of the ALOFT model is given by Baum *et al.* (1994). The model consists of solving the conservation equations of mass, momentum and energy that describe the steady-state, convective transport of heated gases and combustion products introduced into the atmosphere by a steadily burning fire. The fire itself is not modeled, but rather the plume of smoke that emanates from it. The purpose of solving the fundamental equations rather than relying on empirical formulae is because traditional models of atmospheric dispersion were not designed to handle the extremely large sources of heat anticipated from the burning of oil. Also, with the development of ever-faster computers, the solution of the fundamental equations becomes much more tractable. Indeed, the calculations described in this paper can be performed on a current generation personal computer in less than one hour.

Even with faster computers, certain approximations must be made to accommodate the solution of the discretized equations on a numerical grid whose resolution is fine enough to capture the mixing of the smoke plume with the surrounding air. By assuming that the terrain is relatively flat and the wind is uni-directional over an area one or two kilometers wide surrounding the fire, the spatial dimension of the governing equations can be reduced from three to two, and the speed of the calculation is increased dramatically. However, the uni-directional wind assumption is no longer valid when the plume is to be tracked over complex terrain. Many regions in Alaska where burning might occur are characterized by mountainous terrain. In the region near Valdez, for example, mountains rise several thousand meters within a few kilometers of the shore. For this reason, the original flat terrain algorithm has been supplemented with a complex terrain feature. With this new capability, more realistic, site-specific scenarios can be evaluated. The flat terrain algorithm is still used to track the plume within a few kilometers of the fire where the reduction of the spatial dimension of the governing equations can be exploited to compute the rise of the plume until its stabilization height is reached. At this point, three-dimensional governing equations can be solved to provide a wind field over the complex terrain. The Lagrangian particles that represent the smoke particulate or other combustion products are introduced into the atmosphere by the flat terrain plume rise calculation, and are then transported through the three-dimensional flow field. Figure 1 demonstrates the combination of the two models.

The computational requirements necessary to generate a three-dimensional wind field are greater than those required by the flat terrain calculation. Whereas the flat terrain calculations require 10 to 15 minutes of CPU time and roughly 10 megabytes of memory on current generation PCs, the complex terrain feature requires two to three times as much CPU time and memory. Of course, the requirements demanded by either version of the model depend on the desired resolution of the spatial grid. The numbers cited here are typical for simulations performed in the present study.

An obvious question to ask is why not use the three-dimensional algorithm to compute the both the plume rise and its downwind dispersion, eliminating the need to use



**FIGURE 1: Simulation of three smoke plumes originating offshore, demonstrating the flat terrain and complex terrain algorithms.**

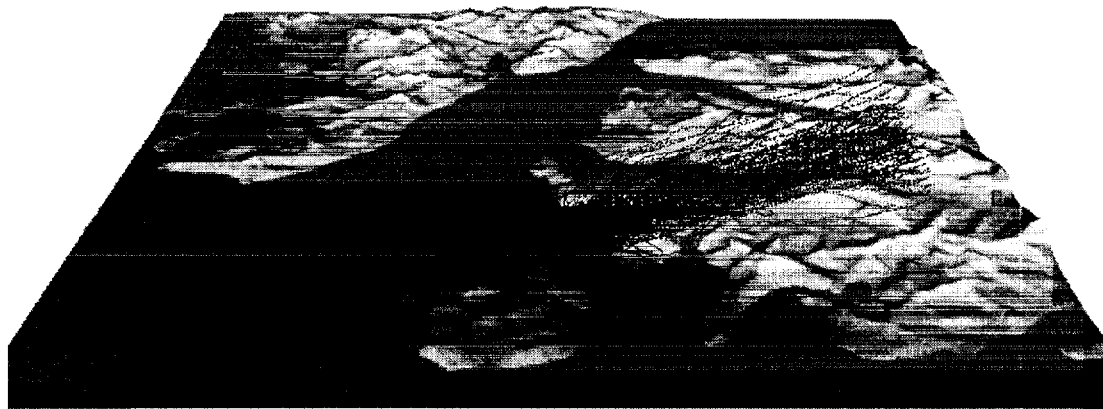
two algorithms? The answer has to do with spatial resolution. The spatial resolution of the three-dimensional complex terrain algorithm is on the order of hundreds of meters because the overall domains of interest are tens of kilometers on a side and several kilometers high. Gridding this volume requires hundreds of thousands of computational cells, depending on how the mesh is arranged. This is the limit of most desktop workstations. Finer grid resolution would require too much time to make the many calculations necessary to consider the wide variety of burn and terrain types. Thus, with a spatial resolution on the order of 100 m, it is not possible to resolve an individual smoke plume as it rises into the atmosphere with the complex terrain algorithm. However, the 5 to 10 m resolution of the plume rise algorithm adequately describes the rise and stabilization of the plume, after which the Lagrangian particles representing smoke particulate can be transported through the three-dimensional wind field.

### **3.0 Applications in Alaska**

The original application of the ALOFT model to the problem of *in situ* burning in Alaska (McGrattan *et al.*, 1995; McGrattan *et al.*, 1996) considered the rise and dispersion of a smoke plume from a single burn over water and/or flat coastal areas. The improvements made to the model now enable site-specific simulations of one or more burns. These additional features of complex terrain and multiple plumes greatly increase the applicability of the ALOFT model, but also increase the number of possible burn scenarios. Obviously, it is impossible to consider every mile of Alaskan coastline under every possible weather condition. Thus the strategy adopted in the study was to

first consider several of the many spill response drills conducted in Alaska over the past decade. The location and meteorological conditions of the sites were used as input to the model. For the purpose of consistency, each simulation assumes the same size fire. The fuel is ANS crude, burning at a rate of  $160 \text{ m}^3/\text{h}$  (1,000 bbl/h). The area of the fire necessary to consume this much oil is about  $760 \text{ m}^2$ , the total energy output of the fire is about 1,300 MW, and the smoke yield is assumed to be 13%. It is also assumed that the oil is contained in a single boom.

Figure 2 presents a three-dimensional view of the results of a typical simulation. A smoke plume originating near Bligh Island, Prince William Sound is shown blowing

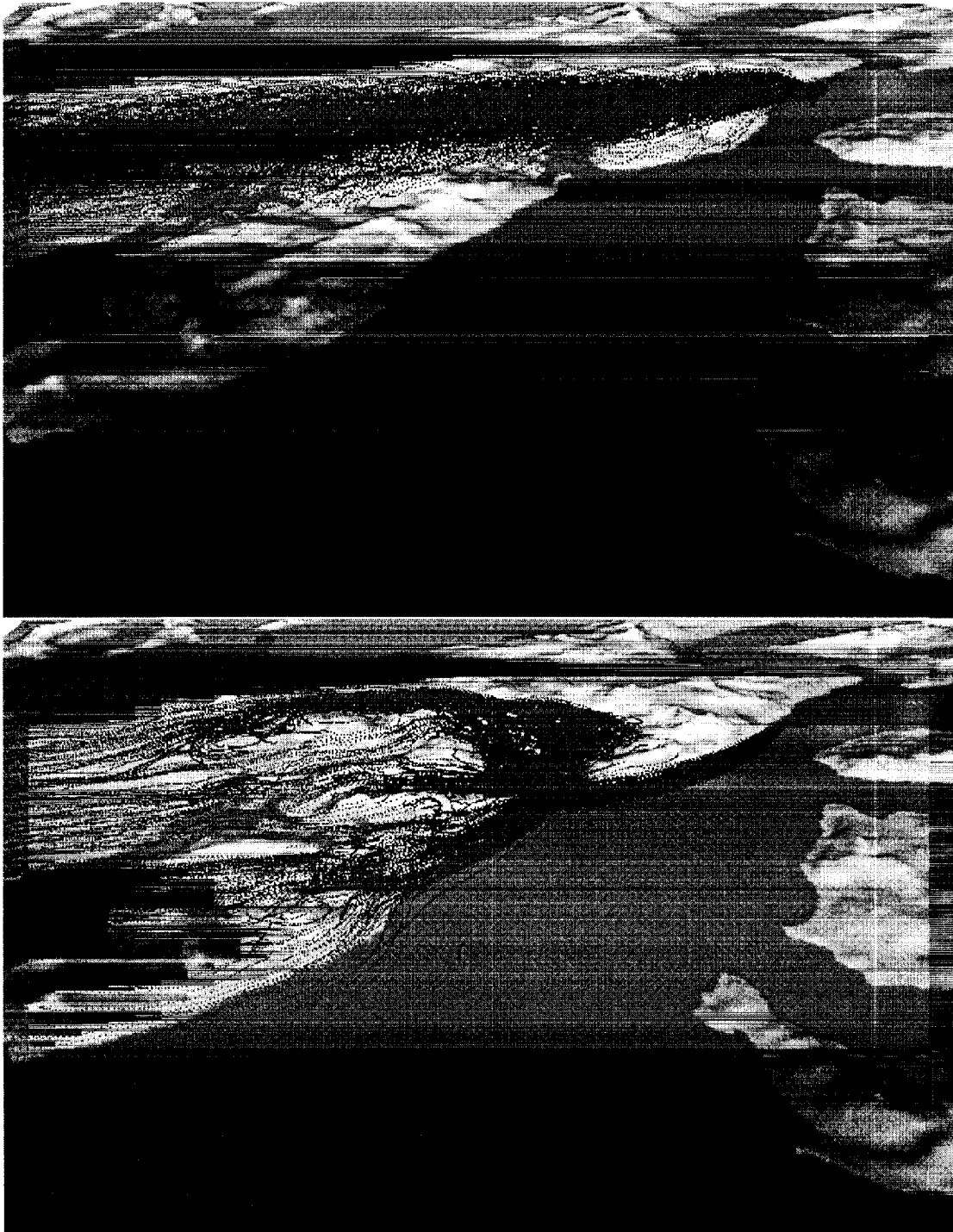


**FIGURE 2: Three-dimensional view of simulated smoke plume originating off Bligh Island, Prince William Sound. Note the increased scattering of the particulate over the land due to the increased wind fluctuations.**

towards Port Valdez. Over water, the wind fluctuations are generally less than those over land, and this is reflected in a more cohesive plume over the water. As the plume approaches the shore, there is more scattering of the particulate due to the increase in the atmospheric turbulence. Depending on the height of the plume above the sea surface, there is the possibility of increased ground level concentration due to what is called fumigation. This occurs when the elevated smoke plume which originates in stable air offshore meets the terrestrial mixing layer formed by the warmer land surface.

Temperature and wind speed profiles are taken from a data base of radiosonde soundings (Schwartz *et al.*, 1995). Turbulence is introduced into the calculation by randomly perturbing the Lagrangian particle trajectories to mimic the effect of the spatially and temporally varying atmosphere. The terrain data required by the model is extracted from a 3 arc second database maintained by the US Geological Survey, EROS Data Center<sup>2</sup>. In Alaska, 3 arc seconds is equivalent to roughly 100 m, and this is sufficient resolution for the simulations performed because the horizontal grid spacing varies from 200 to 400 m. The spacing in the vertical varies from about 40 m at the ground to several hundred meters at an altitude of about 5 km. Further details may be found in McGrattan *et al.* (1997).

<sup>2</sup>The Earth Resources Observation Systems (EROS) Data Center, located in Sioux Falls, South Dakota, is a data management, systems development, and research field center of the US Geological Survey's National Mapping Division. One of the Center's activities is to maintain an on-line data base of digitized maps.



**FIGURE 3: Three-dimensional views of smoke plumes originating in the Valdez Narrows. The top plume represents a case where the Froude number,  $U_0/(N_0 h)$ , is large. The bottom figure is for a case where the Froude number is small.**

As an example of the methodology, consider a burn that takes place at the point where the Valdez Arm narrows to form the entrance to Port Valdez, known as the Valdez Narrows. This water way is surrounded by very steep terrain, and even if the prevailing wind direction is known, it is very difficult to predict the local wind field. Consider the two simulations shown in Figure 3. The winds are blowing out of the northeast, but the wind speed and temperature profiles are different. The top figure is an example of a nearly neutrally stratified atmosphere, whereas the bottom figure is an example of a highly stable atmosphere. In the case of the stable atmosphere, the Valdez Arm forms a channel that traps much of the smoke plume in a swath that hugs the western shoreline. The great difference in the plume trajectories, and the ground level concentration footprints as well, is due to the difference in meteorological conditions. The temperature lapse rate in the first case is very nearly adiabatic and the Brunt-Väisälä frequency<sup>3</sup> is very small. This essentially rids the atmosphere of the effects of the density stratification which for more stable atmospheres tends to suppress vertical motion induced by terrain obstacles. Thus, in the first case where the atmosphere is neutrally stratified, the terrain plays less of a role in the plume's trajectory. Contrast this with the bottom figure. Here the atmosphere is very stable, and the Brunt-Väisälä frequency is relatively large. In this case, vertical motion is severely suppressed, forcing the air flow to go around rather than over the terrain obstacles. Indeed the plume winds its way through the various passageways between the larger mountain peaks, leading to greater concentrations near the surface. An excellent description of stratified flow past three-dimensional obstacles is given by Smolarkiewicz and Rotunno (1989). They characterize the tendency of the fluid to go around rather than over an obstacle in terms of a Froude number<sup>4</sup> given as  $Fr = U_0 / (N_0 h)$ , where  $U_0$  is the prevailing wind speed,  $N_0$  is the characteristic Brunt-Väisälä frequency, and  $h$  is the characteristic height of the terrain obstacle(s). Low values of this parameter (less than 0.5) yield flows characterized by small vertical displacements and the appearance of stagnation regions on both the windward and leeward sides of the obstacle. High values of the Froude number yield flows that tend to pass over, rather than around, mountainous terrain. Not surprisingly, high values of the Froude number correspond to high values of the ventilation factor<sup>5</sup>, and low Froude numbers correspond to low ventilation factors. Thus, as a rough measure of the impact of terrain on flat terrain plume calculations, the ventilation factor is important.

To extract more quantitative information from these calculations, a single figure is generated for each showing the near-ground concentration of smoke particulate (hour-

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<sup>3</sup>the Brunt-Väisälä frequency  $N$  is defined in terms of the temperature profile of the atmosphere  $T_0(z)$

$$\frac{N^2}{g} = \frac{1}{T_0} \left( \frac{dT_0}{dz} + \frac{g}{c_p} \right)$$

where  $z$  is the altitude,  $g$  is the acceleration of gravity, and  $c_p$  is the specific heat of the air. When  $N$  is very small, the atmosphere is very nearly adiabatic. When it is large, the atmosphere is highly stratified.

<sup>4</sup>Froude numbers represent the ratio of inertial forces to gravitational forces in buoyancy-driven flows.

<sup>5</sup>The ventilation factor is the product of the wind speed and the mixing layer depth of the atmosphere. The mixing layer depth refers to the height of the planetary boundary layer, the region of the atmosphere adjacent to the earth's surface characterized by continuous and vigorous turbulence. Its upper edge is sometimes well defined by a temperature inversion, but in other cases, it is less clearly defined, especially in the presence of large, active cumulus clouds. The ventilation factor provides a rough measure of the level of turbulence in the atmosphere. The higher the value, the more "dispersive" the atmosphere.

averaged) and wind field. Figures 4 and 5 summarize the results of the simulations shown in the top and bottom of Figure 3, respectively. The legend at the top of the map displays the atmospheric sounding information used for the simulation, the distance scale, the ventilation factor, the prevailing wind direction, and the rate at which the oil is burning. The ground-level particulate concentration is presented using gray scale contours. Here, ground-level concentration refers to a spatial average spanning the height (about 40 m) and width (about 200 m) of a ground-level numerical grid cell, and a temporal average over a time period of about one hour.

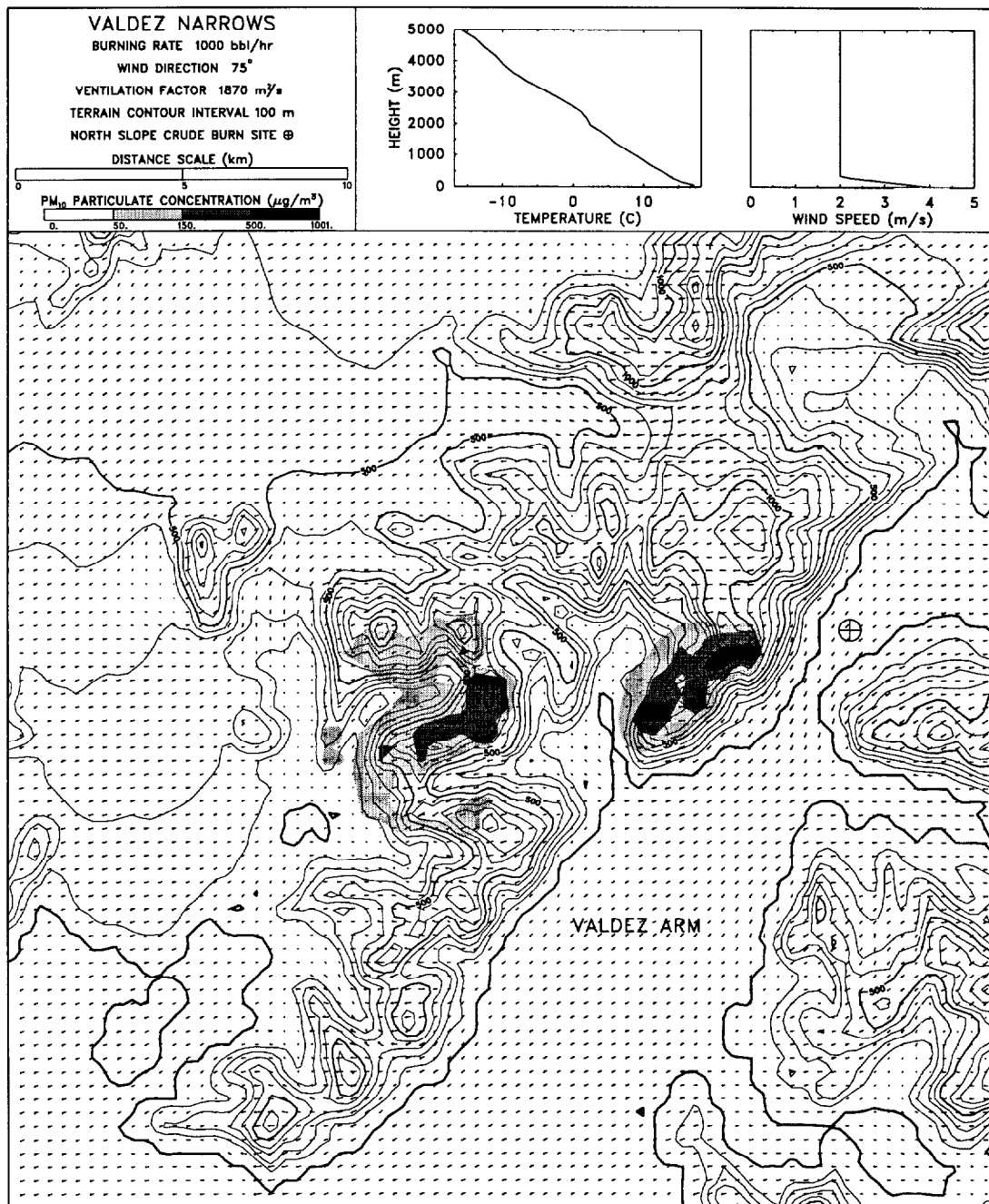
#### 4.0 Summary of Results

Using the ALOFT model, dozens of spill scenarios have been considered for various regions of Alaska, under various meteorological conditions. The objective of the exercise was to develop some simple rules with which to estimate the downwind extent of combustion products in excess of ambient air quality standards. Of all the many parameters that were considered, the terrain height and mixing layer depth were the most important in determining the concentrations expected near the ground. The combustion product most likely to violate ambient air quality standards is PM<sub>10</sub> particulate, and the guideline recommended for *in situ* burning is 150  $\mu\text{g}/\text{m}^3$  averaged over one hour.

**TABLE 1: Distance (km) from a fire consuming 160 m<sup>3</sup>/h (1,000 bbl/h) beyond which the hour-averaged ground level concentration of PM<sub>10</sub> falls below 150  $\mu\text{g}/\text{m}^3$ . Terrain Height and Mixing Layer Depth are relative to the altitude of the burn site. Modifications to these distances to account for different fire sizes and PM standards can be made according to the formula given by Eq. (1).**

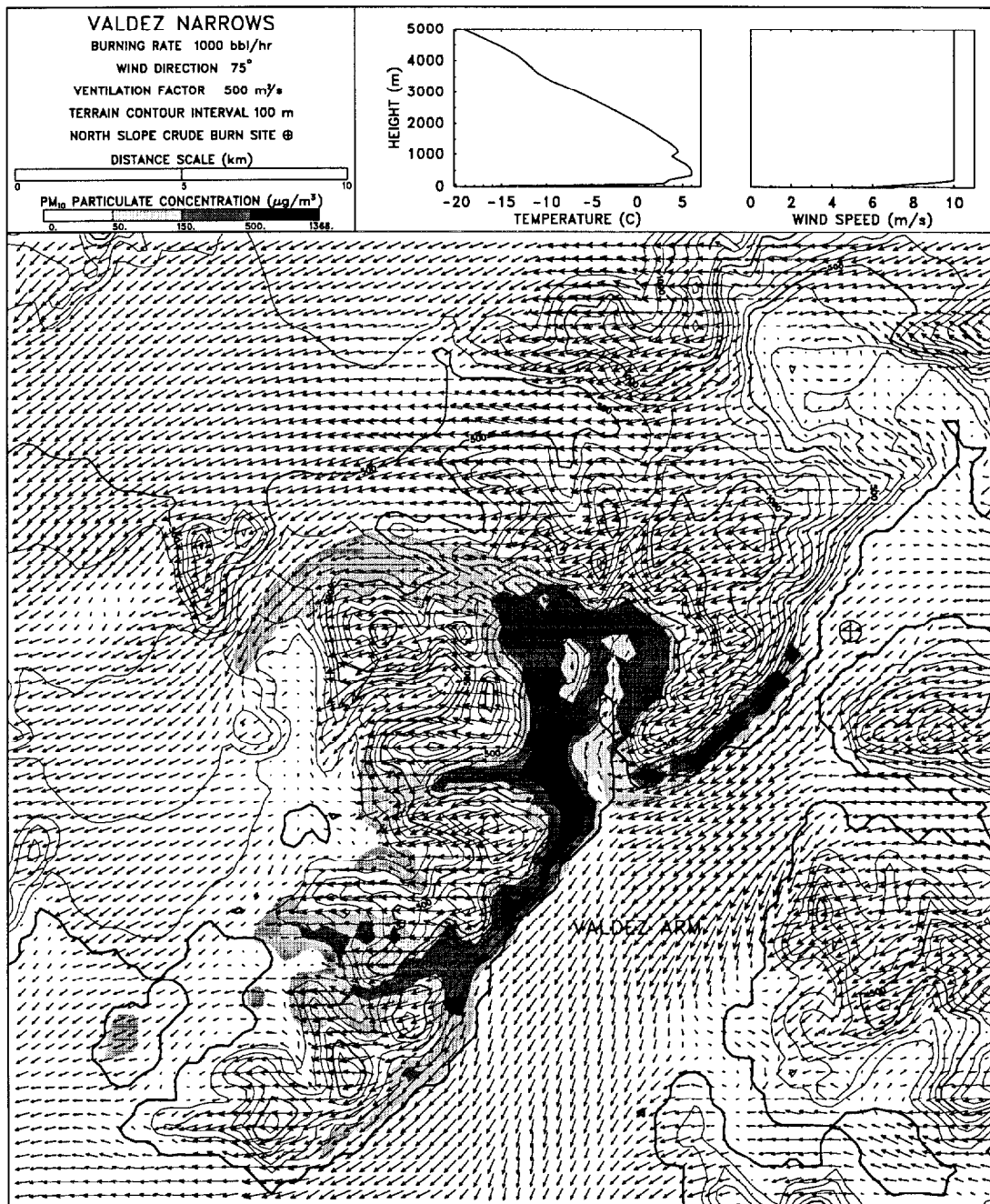
Terrain Height (m)	Mixing Layer Depth (m)				
	0–100	100–250	250–500	500–1,000	> 1,000
0–25 (“Flat Terrain”)	5	4	3	2	1
25–250	10	8	6	4	3
250–500	15	12	10	8	5
> 500	20	17	15	12	10

The simulations can be summarized in terms of the distance beyond which the PM<sub>10</sub> concentration falls below regulatory thresholds. The two most important factors determining this distance are the terrain height and the mixing layer depth *relative* to the elevation of the burn site. Taking the 160 m<sup>3</sup>/h (1,000 bbl/h) burn as an upper limit for a single fire, 130 g/kg as the particulate emission factor, and 150  $\mu\text{g}/\text{m}^3$  as the hour-averaged concentration threshold, Table 1 lists the maximum distance as a function of terrain height and mixing layer depth. The mixing layer depth is loosely correlated with the temperature lapse rate, and the wind speeds considered were in the range from 1 to 12 m/s. Note that the first row of the table corresponds to relatively flat terrain. The maximum distance estimates can be modified to account for changes in the fire size, emission factor, concentration threshold, offshore burns, and multiple burns. If the given burn scenario calls for something other than a single fire on land consuming 160 m<sup>3</sup>/h (1,000 bbl/h), or the ground level particulate criteria is something other than



**FIGURE 4: Footprint of simulated smoke plume originating off the Valdez Narrows, where the atmosphere is neutrally stratified.**





**FIGURE 5: Footprint of simulated smoke plume originating in the Valdez Narrows, where the atmosphere is very stable.**

150  $\mu\text{g}/\text{m}^3$ , or the particulate emission factor is different than the 130 g/kg appropriate for  $\text{PM}_{10}$  (see Table 2), then the distance from Table 1,  $D_{\text{table}}$ , should be modified according to the following formula

$$D = D_{\text{table}} + 7 \ln \left[ (\# \text{ of burns}) \frac{150}{\rho_c} \frac{\text{EF}}{130} \left( \frac{\text{BR}}{160} \right)^{\frac{1}{3}} \right] + \frac{d}{2} \quad \text{km} \quad (1)$$

The expression “(# of burns)” refers to independently burning patches of oil separated by at least 100 m. Superposition of ground level concentration is applied in these cases. The critical hour-averaged concentration  $\rho_c$  should be expressed in units of  $\mu\text{g}/\text{m}^3$ . The emission factor EF should be expressed in units of g/kg. The Burning Rate BR is

**TABLE 2: Emission factors and cumulative mass fraction for several particulate sizes. The cumulative mass fraction is the percentage of the total particulate mass associated with particles whose effective diameters are less than or equal to the given PM value. These results are based on several large scale burns of Louisiana crude (Evans *et al.*, 1993), the Newfoundland offshore burns of Alberta Sweet Mixed Blend (Ross *et al.*, 1996; Walton *et al.*, 1994), and some laboratory scale burns of Alaska North Slope and Cook Inlet crudes (McGrattan *et al.*, 1995).**

Particulate Size Distribution		
Particulate Size ( $\mu\text{m}$ )	Emission Factor (g/kg)	Cumulative Mass (%)
Total Particulate	150	100
$\text{PM}_{10}$	130	87
$\text{PM}_5$	100	67
$\text{PM}_{3.5}$	87	58
$\text{PM}_{2.5}$	82	55
$\text{PM}_{1.0}$	75	50

expressed in units of  $\text{m}^3/\text{h}$  *per fire*. It is assumed that in the case of multiple burns, all the fires are of comparable size. Note that the Burning Rate, BR, can be expressed in terms of the burn area, burning rate or heat release rate as long as the value of the denominator (here given as 160  $\text{m}^3/\text{h}$ ) is consistent. In cases where the plume originates a distance  $d$  offshore, the distance  $d/2$  is added to the overall distance estimate from the table  $D_{\text{table}}$  to account for the fact that the plume is subjected to less atmospheric turbulence over water.

An example of how to use Eq. (1) is to determine how the distances given in Table 1 would be modified if the ambient air quality standard for particulate changed from 150  $\mu\text{g}/\text{m}^3$  to 50  $\mu\text{g}/\text{m}^3$  for  $\text{PM}_{2.5}$  instead of  $\text{PM}_{10}$ . In this case, Eq. (1) would read

$$D = D_{\text{table}} + 7 \ln \left[ \frac{150}{50} \frac{82}{130} \right] = D_{\text{table}} + 4.5 \quad \text{km} \quad (2)$$

Thus, the change in the particulate standard would increase the distances of Table 1 by 4.5 km.

Note that the distance given by (1) may be negative, in which case the distance from Table 1 would be reduced. However, this distance should never be reduced to less than one kilometer from the fire because of the unpredictable, transient nature of the near-field environment that is not accounted for by the quasi-steady state model. This includes low traveling smoke during fire ignition and extinction.

## 5.0 Conclusion

The strategy from the beginning of the development of the ALOFT model has been to work from the fundamental conservation equations that describe the introduction of hot gases and particulate matter into the atmosphere. The justification for this approach is manifested by the extremely complicated flow simulations of smoke dispersal over the rugged terrain of Alaska. There simply is no other way to simulate these flow patterns except by solving the fundamental conservation equations of fluid mechanics. Empirical correlations become hopelessly awkward to apply as the number of degrees of freedom in the problem increases with the introduction of realistic meteorology and terrain. Fortunately, the rapid development of relatively inexpensive, powerful computers has made it possible to compute the solution to the equations of motion that govern the transport of pollutants in the lower atmosphere at a resolution that is comparable to that of the underlying terrain data.

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